

Resolved spectroscopy of gravitationally lensed galaxies: recovering coherent velocity fields in subluminal $z \sim 2\text{--}3$ galaxies

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ABSTRACT

We present spatially resolved dynamics for six strongly lensed star-forming galaxies at $z = 1.7\text{--}3.1$, each enlarged by a linear magnification factor of $\sim \times 8$. Using the Keck laser guide star AO system and the OH-Suppressing Infra-Red Imaging Spectrograph integral field unit spectrograph, we resolve kinematic and morphological detail in our sample with an unprecedented fidelity, in some cases achieving spatial resolutions of $\simeq 100$ pc. With one exception our sources have diameters ranging from 1 to 7 kpc, integrated star formation rates of $2\text{--}40 M_{\odot} \text{ yr}^{-1}$ (uncorrected for extinction) and dynamical masses of $10^{9.7\text{--}10.3} M_{\odot}$. With this exquisite resolution, we find that four of the six galaxies display coherent velocity fields consistent with a simple rotating disc model. Our model fits imply ratios for the systemic to random motion, $V_c \sin i / \sigma$, ranging from 0.5 to 1.3 and Toomre disc parameters $Q < 1$. The large fraction of well-ordered velocity fields in our sample is consistent with data analysed for larger, more luminous sources at this redshift. We demonstrate that the apparent contradiction with earlier dynamical results published for unlensed compact sources arises from the considerably improved spatial resolution and sampling uniquely provided by the combination of adaptive optics and strong gravitational lensing. Our high-resolution data further reveal that all six galaxies contain multiple giant star-forming H II regions whose resolved diameters are in the range 300 pc to 1.0 kpc, consistent with the Jeans length expected in the case of dispersion support. From the kinematic data, we calculate that these regions have dynamical masses of $10^{8.8\text{--}9.5} M_{\odot}$, also in agreement with local data. However, the density of star formation in these regions is $\sim 100\times$ higher than observed in local spirals; such high values are only seen in the most luminous local starbursts. The global dynamics and demographics of star formation in these H II regions suggest that vigorous star formation is primarily governed by gravitational instability in primitive rotating discs. The physical insight provided by the combination of adaptive optics and gravitational lensing suggests it will be highly valuable to locate many more strongly lensed distant galaxies with high star formation rates before the era of the next-generation ground-based telescopes when such observations will become routine.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION

Studies of star-forming galaxies at high redshift ($z > 1.5$) over the past decade have mapped the demographics of the populations as a whole yielding valuable data on their integrated star formation rates (SFRs), stellar and dynamical masses, metallicities and morphologies (Shapley et al. 2001, 2003; Reddy & Steidel 2004; Erb et al. 2006; Law et al. 2007a). From these data, a consistent picture of the development of the comoving density of star formation and its con-

tribution to the present-day stellar density has emerged (Dickinson et al. 2003; Hopkins & Beacom 2006). Following a rapid rise in activity at early times, corresponding to the redshift range $2 < z < 6$, the SFR has declined markedly over the past 8 Gyr corresponding to the interval $0 < z < 1$. Of particular interest is the relationship between sources observed at the time close to the peak epoch of star formation, $z = 2\text{--}3$ and the population of massive galaxies observed today.

Recent theoretical work has focused on the mechanisms via which early galaxies assemble their stars and evolve morphologically to the present-day Hubble sequence. Minor mergers and cold

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stream gas accretion have emerged as a possible means of building discs, central bulges and elliptical galaxies from early star-forming Lyman break galaxies (LBG; Dekel, Sari & Ceverino 2009; Brooks et al. 2009). These models of galaxy evolution rely on simple descriptions of complex physical processes such as gas cooling, star formation and feedback mechanisms. It is therefore crucial to undertake relevant observations to constrain these processes. The most direct observational route to making progress is high quality resolved spectro-imaging of early galaxies which can be used to determine both their dynamical state and the distribution of star-formation.

Integral field unit (IFU) spectroscopy of nebular emission lines is now yielding valuable kinematic data for a growing sample of luminous high-redshift star-forming galaxies (Förster Schreiber et al. 2006, 2009; Genzel et al. 2006, 2008; Bouché et al. 2007; Law et al. 2007b, 2009; Wright et al. 2009). Although the galaxies observed so far do not yet in any way constitute a complete well-defined sample, some important results have emerged. The data reveal a mix of dispersion-dominated systems, rotating systems and major mergers with the common observation that all galaxies studied so far show relatively high velocity dispersions of $\sim 50\text{--}100\text{ km s}^{-1}$. A larger fraction of the more massive ($M_{\text{dyn}} \gtrsim 10^{11} M_{\odot}$) galaxies appear to be rotationally supported, with lower mass galaxies ($M_{\text{dyn}} \lesssim 10^{10} M_{\odot}$) tending to have dispersion-dominated kinematics (Law et al. 2009).

However, these studies are hampered by the poor spatial resolution inherent in studies of distant star-forming galaxies whose typical sizes are $\simeq 1\text{--}5\text{ kpc}$. Even with adaptive optics on an $8\text{--}10\text{ m}$ aperture, the physical resolution is limited to full width at half-maximum (FWHM) $\gtrsim 1\text{ kpc}$ which means only a few independent resolution elements. Consequently it is unclear whether the velocity shear observed in the smaller $2\text{--}5\text{ kpc}$ sources arises from rotation or merging. Moreover, although there are suggestions that distant star-forming regions have sizes much larger than those of local H II regions (Elmegreen & Elmegreen 2005), the claim remains uncertain since the distant regions are not properly resolved. Thus, the diffraction limit of the current generation of optical/infrared telescopes limits progress, even with all the adaptive optics tools of the trade.

Fortunately, sources which undergo strong gravitational lensing are enlarged as seen by the observer and can thus be studied at much higher physical resolution in their source plane (Nesvadba et al. 2006; Swinbank et al. 2007). This improvement in physical resolution enables us to better distinguish various forms of velocity field and to examine the properties of star-forming giant H II regions. A convincing demonstration of the benefits of lensing as applied to this topic was the work of Stark et al. (2008) which analysed IFU data on a $z = 3.07$ galaxy magnified in area by a factor of 28 times demonstrating resolved dynamics on $\simeq 100\text{ pc}$ scales. This represents an order of magnitude improved sampling compared to the earlier studies cited above.

Here we present IFU observations of a further five strongly lensed galaxies which we add to the source studied by Stark et al. (2008). In addition to studying the well-sampled kinematic structure of a population of sub- L^* star-forming galaxies at $z \simeq 2$, our fine resolution allows us to examine the size, dynamical mass and luminosity of typical star-forming regions, thereby probing the conditions in which most of the star formation takes place. We find that all of our galaxies contain multiple, distinct star-forming regions. These results offer a preview of the science which will be possible with 30 m class optical/near-infrared telescopes with a diffraction limit comparable to the resolution of our data; they provide the most detailed view to date of typical high-redshift star-forming galaxies.

A plan of the paper follows. In Section 2, we discuss our selection of targets and Keck observations, including the production and use of gravitational lens modelling essential for achieving a high resolution in the source plane. In Section 3, we analyse our spectroscopic results, discussing each object in turn and summarizing the kinematic data. In Section 4, we examine the physical scale of our star-forming regions in comparison to those seen locally. We summarize our conclusions in Section 5. Throughout we use a *Wilkinson Microwave Anisotropy Probe* (WMAP) cosmology (Spergel et al. 2003) with $\Omega_{\Lambda} = 0.73$, $\Omega_{\text{m}} = 0.27$ and $H_0 = 72\text{ km s}^{-1}\text{ Mpc}^{-1}$. All quoted magnitudes are in the AB system unless otherwise noted.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Target selection

Ideally, in considering the selection of high-redshift galaxies for more detailed resolved studies, care would be taken to construct a mass-limited sample, perhaps defined additionally according to the integrated or specific SFR. In practice, even with 10 m class telescopes, studies are limited by the surface brightness distribution of gaseous emission lines as discussed by earlier workers (Förster Schreiber et al. 2006, 2009; Genzel et al. 2006, 2008; Law et al. 2007b, 2009). In examining *gravitationally lensed* systems, which have the unique advantages of probing to less luminous (and presumably more typical) systems, and offering an increased spatial resolution in the source plane, an additional criterion is the reliability of the mass model used to invert the observed data into that of the source plane.

Over the past decade, using the growing archive of *Hubble Space Telescope* (HST), Advanced Camera for Surveys (ACS) and Wide Field Planetary Camera 2 (WFPC2) images of rich clusters (e.g. Blakeslee et al. 2003; Santos et al. 2004; Sand et al. 2005; Stark et al. 2007) and through specific projects such as the MAssive Cluster Survey (MACS; Ebeling, Edge & Henry 2001) and Local Cluster Substructure Survey (LoCuSS; Smith et al. 2005), we have studied a large sample of lensing clusters and undertaken a search within these HST images for promising magnified galaxies (arcs) at high redshift. The clusters presented herein do not in any way represent a well-defined sample and, inevitably, there are biases to those which act as spectacular gravitational lenses.

The distant sources described here were located and assessed via two sequential programmes. First, a comprehensive multi-object spectroscopic campaign involving Keck and the Very Large Telescope (VLT) was used to verify the redshift of the candidate arcs as well as to determine the redshifts of other multiply imaged sources in each cluster in order to construct robust mass models (e.g. Richard et al. 2007). As the follow-up spectroscopy was undertaken at optical wavelengths, for those sources beyond $z \simeq 2$, this provided valuable insight into the strength and distribution of Ly α emission. However, as with previous work (e.g. Shapley et al. 2003), we found that the Ly α line did not necessarily give a good indication of the relative strengths and extended nature of those nebular emission lines ([O II], H β , [O III], H α) critical for resolved studies with laser guide-star assisted adaptive optics (LGS AO). Accordingly, we used the Keck II Near-Infrared Spectrometer (NIRSPEC) in seeing limited mode in a second campaign to ‘screen’ all promising targets in advance of undertaking the more demanding resolved studies with the LGS AO-fed IFU spectrograph OH-Suppressing Infra-Red Imaging Spectrograph (OSIRIS). Once the redshift of the lensed source was known from optical spectroscopy, we usually followed up the source in more than one near-infrared line, in order to

Table 1. Gravitational lens modelling is discussed in Section 2.3. The lensing amplification is non-uniform and highly directional, thus we give the typical linear magnifications μ_1 , μ_2 along the minor and major lensing axes as well as the overall flux magnification μ . The source plane resolution refers to the typical FWHM of a point source in the direction of highest magnification. The photometric bands B , v , V , r , i , I and z are ACS filters F435W, F555W, F606W, F625W, F775W, F814W and F850LP, respectively.

Name	α_{J2000} (^h ^m ^s)	δ_{J2000} ([°] ['] ^{''})	z	t_{exp} (ks)	Target list Emission lines; OSIRIS filter	$\mu_1 \times \mu_2$	μ	FWHM (pc)	<i>HST</i> ACS photometry and proposal IDs
Cl0024+1709	00 26 34.43	+17 09 55.4	1.680	16.5	H α , [N II]; Hn5	0.8×1.7	$1.38 \pm .15$	820	B,v,r,i,z,GO-10491
MACSJ0451+0006	04 51 57.27	+00 06 20.7	2.014	14.4	H α , [N II]; Kn1	1.3×37.0	49 ± 11	60	V,I,GO-10491,GO-10875
MACSJ0712+5932	07 12 17.51	+59 32 16.3	2.648	16.2	H α , [N II]; Kc5	1.5×18.7	28 ± 8	90	V,I,GO-10491,GO-10875
MACSJ0744+3927	07 44 47.82	+39 27 25.7	2.209	14.4	H α , [N II]; Kn2	1.9×8.6	16 ± 3	310	v,I,GO-9722
Cl0949+5153	09 52 49.78	+51 52 43.7	2.394	19.2	[O III]; Hn4	1.2×6.0	7.3 ± 2.0	350	V,GO-9270
MACSJ2135–0102	21 35 12.73	–01 01 43.0	3.074	21.6	H β , [O III]; Kn1	3.5×8.0	28 ± 3	120	V,I,GO-10491

ascertain which would be the most economic tracer of the velocity field.

About 75 per cent of our initial sample of 30 $z > 1.5$ arcs have so far been screened and have suitably close reference stars for tip-tilt correction. In order to achieve an adequate signal to noise with OSIRIS, we used the NIRSPEC data to limit the sample to those with an emission line surface brightness $\gtrsim 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ in a region uncontaminated by night sky emission. As a guide, this surface brightness criterion corresponds to a SFR density $> 0.3 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ for H α at $z = 2$. Our sample of six sources is drawn from a list of $\simeq 20$ objects fulfilling these criteria. A full account of the NIRSPEC screening programme and a discussion of the distribution of line strengths found in that survey is given by Richard et al. (in preparation). Key properties for the sample of six objects, which include the source discussed by Stark et al. (2008), are given in Table 1. The ACS images of our lensed targets are given in Fig. 1 and we briefly discuss these below.

Cl0024+1654. Deep optical and near-infrared imaging of the $z = 0.39$ cluster Cl0024+1654 with *HST* reveals five distinct images of a background galaxy originally identified by its blue colour and clumpy ring-like morphology (Colley, Tyson & Turner 1996; Fig. 1). Optical spectroscopy established a redshift of $z = 1.675$ from interstellar absorption lines (Broadhurst et al. 2000). Near-infrared spectroscopy shows bright, spatially extended H α emission at $z = 1.6795$. To map the velocity field, we observed the counter image north-west of the cluster with OSIRIS around the redshifted H α and [N II] $\lambda 6583$ emission.

MACSJ0451+0006. The *HST* ACS V - and I -band imaging of MACSJ0451+0006 shows a striking, multiply imaged arc $\simeq 30$ arcsec east of the brightest cluster galaxy (Fig. 1). Follow-up spectroscopy with the Focal Reducer and Low Dispersion Spectrograph (FORS) on the VLT confirmed a redshift of $z = 2.008$ via the identification of Ly α and ultraviolet (UV) interstellar medium absorption lines (Si II λ 1260, O I λ 1303, C IV λ 1549 and Si IV λ 1400) and He II λ 1640 and C III λ 1908.7 in emission (PID: 078.A-0420). Follow-up observations targeting the nebular H α emission with the NIRSPEC long-slit spectrograph on Keck II showed strong, spatially extended H α at a redshift of 2.0139 ± 0.0001 (Richard et al., in preparation).

MACSJ0712+5932. *HST* V - and I -band imaging of MACSJ0712+5932 reveals a prominent triply imaged background galaxy. Each image of the galaxy images clearly comprises two prominent clumps with surface brightness $\mu_V > 23 \text{ mag arcsec}^{-2}$ within a diffuse halo (Figs 1 and 2). Follow-up near-infrared spectroscopy (Richard et al., in preparation) shows strong nebular H α ,

H β and [O III] $\lambda\lambda 5007, 4959$ emission at $z = 2.6462$, concentrated in the UV-bright regions.

MACSJ0744+3927. *HST* V - and I -band imaging of MACSJ0744+3927 reveals a singly imaged arc approximately 15 arcsec west of the cluster centre. The optical redshift $z = 2.207$ obtained via identification of strong Ly α absorption and multiple rest-frame UV absorption lines was later confirmed by the detection of strong H α and [N II] emission at $z = 2.209$ with NIRSPEC.

Cl0949+5153. The *HST* V -band image of Cl0949+5153 shows a clumpy, elongated singly imaged arc resolved into two diffuse components (Fig. 1). Further spectroscopy around the redshifted nebular emission lines shows extended H α , H β and [O III] $\lambda\lambda 5007, 4959$ emission at $z = 2.393$.

MACSJ2135–0102. For completeness, we also include in our sample discussion of the velocity field of the lensed multiply imaged LBG at $z = 3.07$ in MACSJ2135–0102 (also known as the ‘Cosmic Eye’ due to its lensed morphology; Stark et al. 2008). Multi-wavelength studies have shown that the source is a L^* LBG with a stellar age of 80–300 Myr, SFR = 40–60 $\text{M}_{\odot} \text{ yr}^{-1}$, and stellar mass of $M_* = 6 \pm 2 \times 10^9 \text{ M}_{\odot}$ (Coppin et al. 2007; Siana et al. 2009).

2.2 OSIRIS observations and data reduction

Detailed two-dimensional spectroscopic observations of the targets listed in Table 1 were made with the near-infrared integral field spectrograph OSIRIS (Larkin et al. 2006) on the 10 m Keck II telescope using the laser guide star adaptive optics (LGS AO) system (Wizinowich et al. 2006) to correct for atmospheric distortion. A suitably bright star ($R < 17$) within ~ 50 arcsec of the target was used for tip-tilt correction. We used the 100 mas pixel scale in all observations which provides a field of view of at least 3.2×6.4 arcsec. Narrow band H and K filters (Table 1) were selected to target the H α or [O III] $\lambda 5007$ emission line at a spectral resolution $R \simeq 3600$, corresponding to FWHM $\simeq 6 \text{ \AA}$ in the K band. MACSJ2135–0102 and MACSJ0451+0006 were observed on 2007 September 02 and 03 whilst the remaining targets were observed between 2008 November 27 and 30.

All observations were taken in 0.6–1.3 arcsec seeing. Before observing each arc, we took short exposures of the tip-tilt reference star to centre the IFU pointing. The tip-tilt exposures were also used for flux calibration and to calculate the point spread function. Gaussian fits to the point spread functions of the tip-tilt stars yield 0.13–0.20 arcsec FWHM resolution for the 100 mas pixel scale. With smaller pixel scales, the resolution delivered by the LGS AO system was 0.11 arcsec FWHM. Observations of each target were

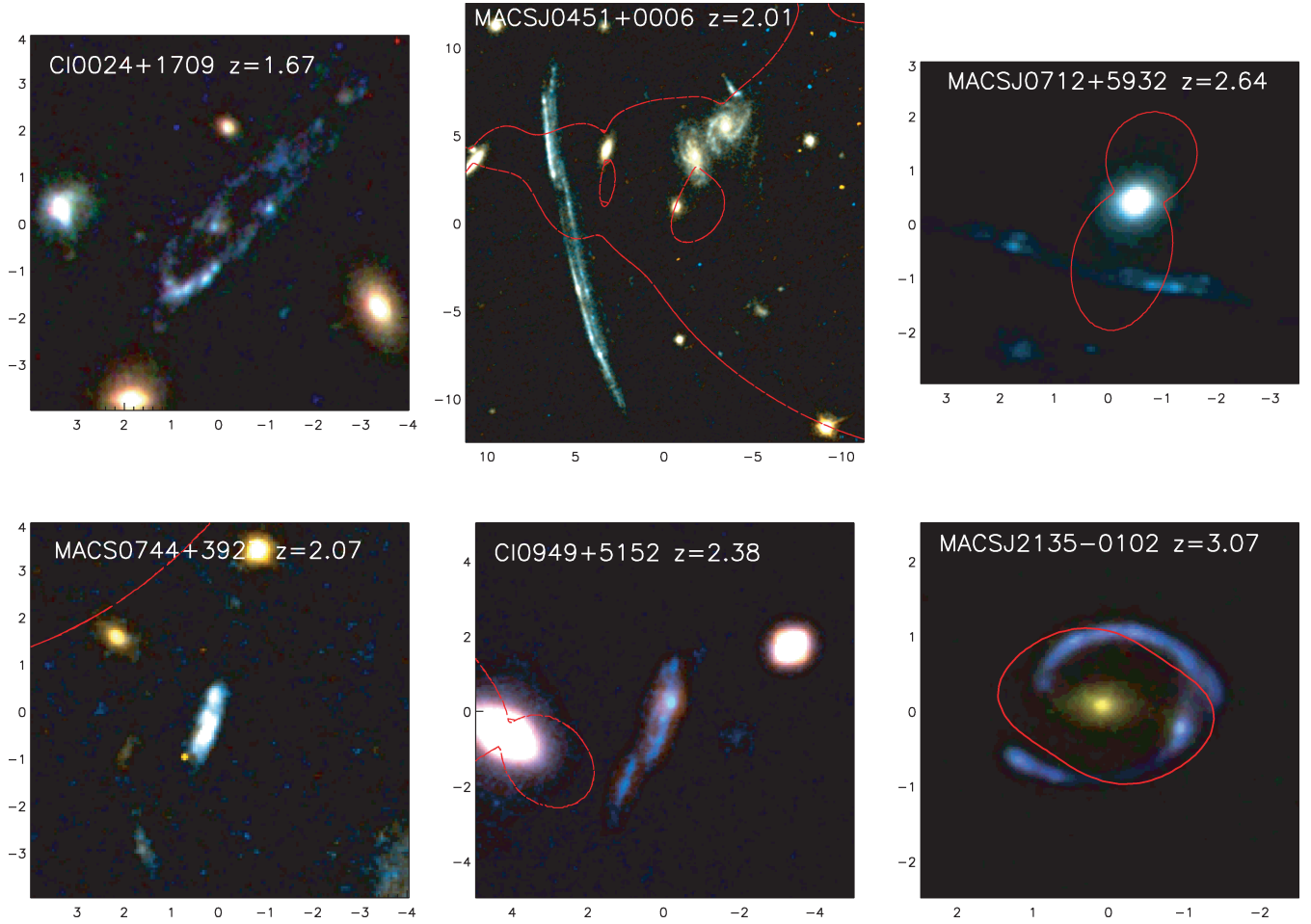


Figure 1. True colour ACS images of the sample derived from the multiband data referred to Table 1. The xy scale is in arcseconds. Critical lines for the redshifts, derived from lens modelling (Section 2.3), are shown in red. The critical line for CI0024+1709 falls outside the image.

done in a standard ABBA position sequence to achieve good sky subtraction. In the case of CI0024+1709 we chopped 8 arcsec to sky, whilst in the remaining cases we chopped the galaxy within the IFU. Individual exposures were 600–900 s and each observing block was 2.4–3.6 ks which was typically repeated three to six times. The total integration time for each object is given in Table 1.

Our data reduction methods closely followed those described in detail by Stark et al. (2008). We used the OSIRIS data reduction pipeline (Larkin et al. 2006) to perform sky subtraction, spectral extraction, wavelength calibration, and form the data cube. To accurately combine the individual data cubes, we created images of the integrated emission line and used the peak intensity to centroid the object. We then spatially aligned and co-added the individual data cubes to create the final mosaic. Flux calibration was performed by equating the flux density of the tip-tilt stars measured from Two Micron All Sky Survey photometry with the observed OSIRIS spectra. We estimate that the uncertainty in flux calibration is typically 10 per cent.

2.3 Gravitational lens modelling

In order to investigate the source plane properties, we must first correct for the distortion and magnification by the cluster lens. We summarize here the ingredients necessary to construct the relevant cluster mass models. We will follow the methodology defined by

earlier relevant articles (Kneib et al. 1993, 1996; Smith et al. 2005; Jullo et al. 2007) within which further details can be found.

Our basic approach is to use the code `LENSTOOL`¹ (Kneib et al. 1993; Jullo et al. 2007) to constrain a parametrized model of the dark matter distribution. For each cluster, the model comprises two components: 1 or 2 cluster-scale dark matter haloes, parametrized with a dual pseudo-isothermal elliptical mass distribution (dPIE; Elíasdóttir et al. 2007), and ~ 50 galaxy-scale dPIE dark matter haloes, centred on massive cluster members occupying the strong lensing region in order to account for the presence of substructure. These galaxy-scale haloes are assumed to have mass properties that follow a scaling relation based on the luminosity of the underlying galaxy, assuming a constant mass-to-light ratio (e.g. Natarajan et al. 1998; Smith et al. 2005).

Details on the construction of each gravitational lens model are given in Dye et al. (2007) for MACS J2135–0102, in Limousin et al. (in preparation) for CI0024+1709 and MACS J0744+3927 and in Richard et al. (in preparation) for the remaining three sources in Table 1. Strong lensing constraints originate from the identification of 2–5 multiply imaged systems per cluster within the various ACS images. We use the astrometric positions and spectroscopic/photometric redshifts of these sources² as individual constraints to

¹ <http://www.oamp.fr/cosmology/lenstool>

² Spectroscopic redshifts are available for a majority of the systems.

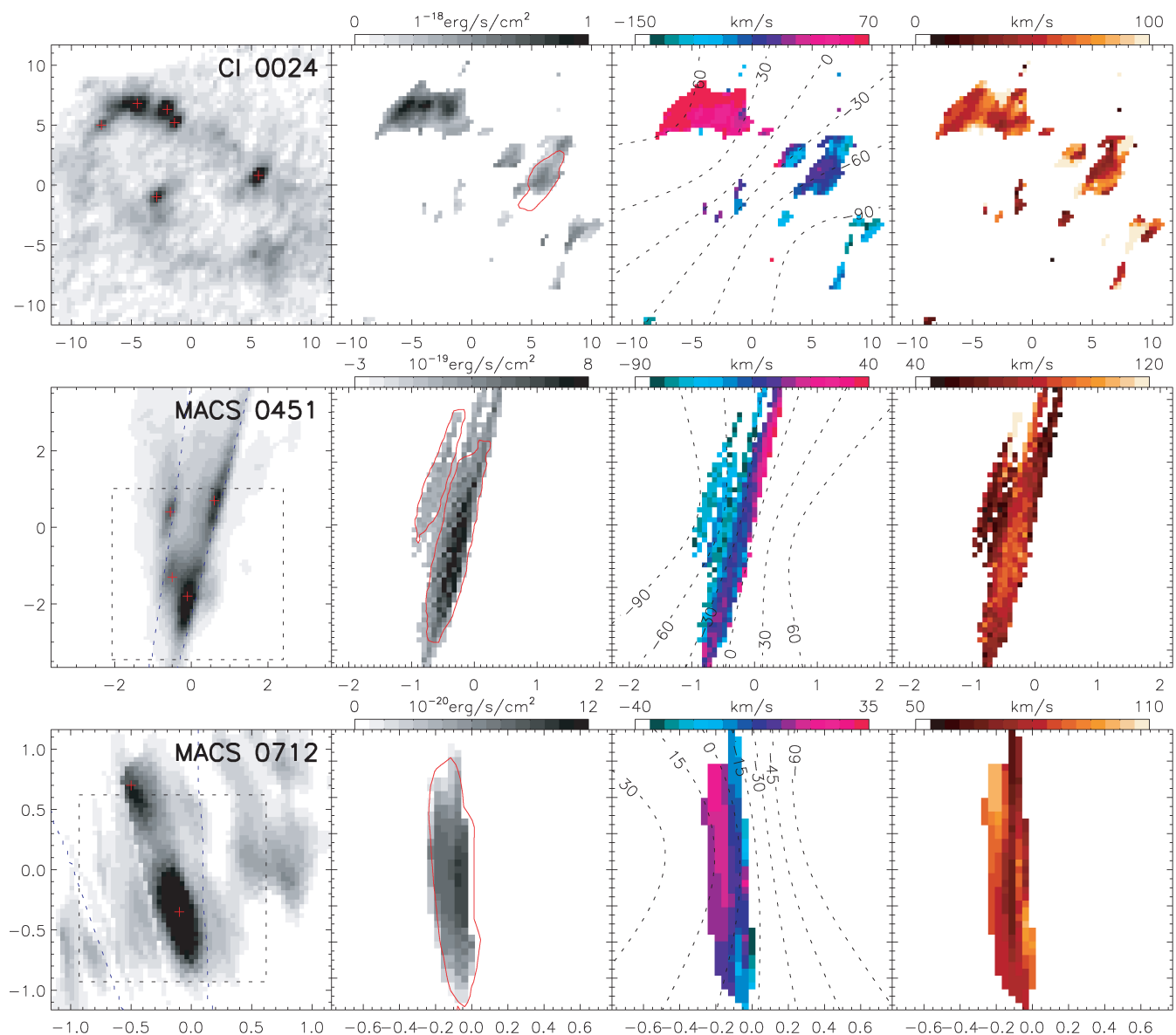


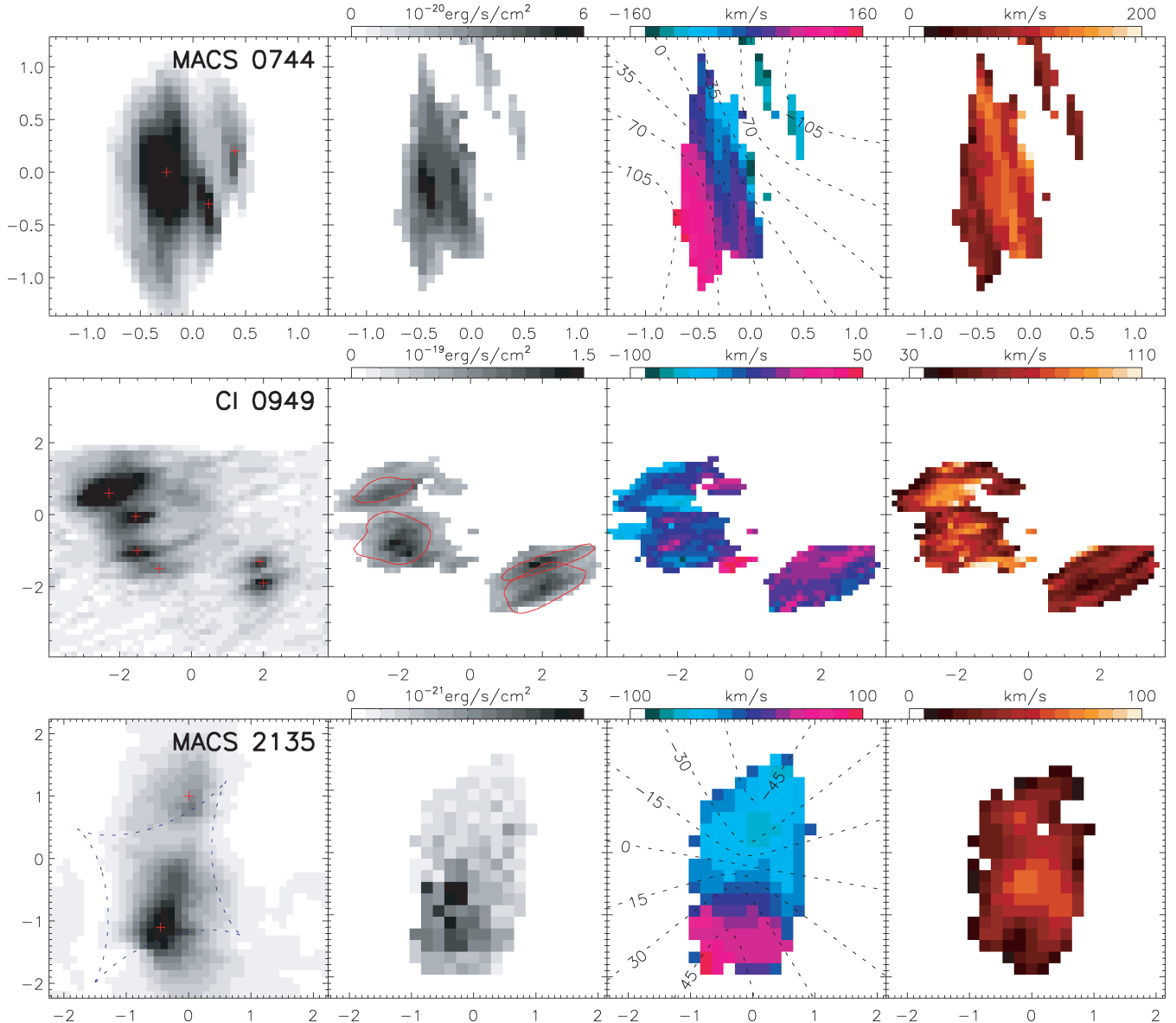
Figure 2. Source plane properties of the lensed galaxy sample. From left-to-right panels in each row: ACS broad-band emission, line intensity, velocity and velocity dispersion derived from the OSIRIS nebular emission line data. Axes are in kpc with 1–2 pixels per OSIRIS resolution element. Each galaxy shows morphological and kinematic structure on scales down to ~ 100 –200 parsec. The nebular line flux distribution is similar to the rest-UV morphology with multiple resolved clumps, shown as red crosses on the ACS images. Red contours on the line intensity maps denote clumps which are spatially extended and unconfused at the $\approx 3\sigma$ flux isophote in narrow-band emission line images, as described in Section 4. Best-fitting disc model contours are shown on the velocity maps for those galaxies whose dynamics are consistent with rotation (Section 3.1). Dashed boxes in the ACS images of MACS J0451 and MACS J0712 indicate the smaller regions for which OSIRIS data are displayed. Caustics are shown as dashed blue lines in the ACS images of multiply imaged arcs.

derive best-fitting parameters on the mass distribution. *LENSTOOL* uses a Markov Chain Monte Carlo (MCMC) sampler to derive a family of mass models suitably fitting the strong lensing constraints, and we use these to derive the uncertainty on each parameter of the mass distribution.

For each of the sources presented in this paper, the best model was then used to derive the geometrical transformation necessary for mapping the image plane coordinates into the source plane. This transformation enables us to reconstruct the *HST* morphology and $H\alpha$ emission line images in the source plane assuming conservation of surface brightness. The spot magnification μ_{xy} and its associated error are computed with *LENSTOOL* at different positions across the object, using the family of mass models from the MCMC sampler.

We can verify this value by computing the total magnification from the ratio of the sizes (or equivalently, the total fluxes) between the image and its source plane reconstruction. As the magnification factor is not isotropic, the angular size of each image is more highly stretched along a specific orientation (Fig. 1) thus affecting our source plane resolution. The linear factors μ_1 and μ_2 of the magnification (with $\mu = \mu_1 \times \mu_2$) together with their associated errors are listed in Table 1. A detailed illustration of the uncertainties of the mass modelling method for MACSJ2135–0102 is given in Stark et al. (2008).

A key parameter in our analysis is the *physical resolution* we achieve in the source plane for each target. To measure this, we use observations of the tip-tilt reference stars. These serve this purpose

Figure 2 – *continued*

well as they are point sources observed with conditions and an instrumental configuration identical to those of our distant targets. We ‘reconstruct’ these stars in the source plane as if they were located at the arc position using the same transformation as for the lensed galaxies, and fit a bivariate Gaussian to the point spread function in order to determine the source plane resolution. The typical FWHM of each arc in the direction of highest magnification is listed in Table 1 and, with the exception of CI0024+1709 which is not highly magnified, varies from 60 to 350 pc with a mean of 200 pc.

3 ANALYSIS

First, we reconstruct the reduced, flux-calibrated data cubes to the source plane using transformations from the gravitational lens models described in Section 2.3. The resulting data cubes were binned such that each spatial pixel corresponded to 0.5–1 FWHM resolution

elements along the direction of highest magnification (Table 1). We fit Gaussian profiles to the strongest emission line ($H\alpha$ or $[O III]$) at each spatial pixel using a weighted χ^2 minimization procedure and determine the two-dimensional intensity, velocity and velocity dispersion maps. To compute the emission line fits we first subtracted the median value at each spatial pixel to remove any source continuum and residual sky background. A blank region of sky within each data cube was used to determine the sky variance spectrum $V(\lambda)$. The spectra to be fit are weighted by $w(\lambda) = V^{-1}$ appropriate for Gaussian noise, so that regions of higher noise (e.g. strong sky emission lines) do not cause spurious fits. We compute the χ^2 statistic for the best-fitting Gaussian as well as for a featureless spectrum [$f(\lambda) = 0$] and require a minimum improvement over the fit with no line of $\Delta\chi^2 = 16$ –25 for the various arcs (i.e. 4–5 σ emission line detection). If this criterion was not met, we averaged the surrounding 3×3 spatial pixels to achieve higher signal to noise. No fit was made if the 3×3 averaging still failed to produce the minimum $\Delta\chi^2$ improvement. We calculated the formal 1σ error bounds

by perturbing the Gaussian fit parameters until the χ^2 increases by 1 from the best-fitting value. In all following sections, we have deconvolved the line widths with the instrumental resolution ($R \simeq 3600$) by subtracting the instrumental resolution in quadrature from the best-fitting Gaussian σ . The resulting source plane intensity, velocity and dispersion fields for the entire sample are shown in Fig. 2 and demonstrate detailed kinematic and morphological properties on scales down to 100–200 pc.

From the source plane nebular emission line intensity and dynamics, we estimate the size, dispersion and dynamical mass of each galaxy. The size is calculated as the maximum diameter from pixels with successful emission line fits, roughly equivalent to a major axis diameter with limiting isophote $\sim 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. The uncertainty is dominated by errors in the lensing magnification and is ≤ 20 per cent. We estimate the global average velocity dispersion of each galaxy as the flux-weighted mean of the fit pixels, $\sigma_{\text{mean}} = \sum \sigma_{\text{pix}} I_{\text{pix}}$ with typical uncertainty of ~ 5 per cent estimated from errors in the fit parameters and the spread of σ in individual pixels. This measurement of the dispersion is not affected by resolved velocity gradients. The six galaxies in our sample all have large $\sigma_{\text{mean}} = 50\text{--}100 \text{ km s}^{-1}$, which is consistent with other resolved observations of non-lensed galaxies at $z \gtrsim 2$ (e.g. Förster Schreiber et al. 2009; Law et al. 2009; Lehnert et al. 2009).

3.1 Kinematic modelling

To test whether the kinematics of each galaxy are consistent with a rotating system, and to estimate the inclination of any discs, we construct and fit simple disc models to the observed velocity fields. The disc model for MACSJ2135–0102 is discussed in detail by Stark et al. (2008), and we follow a similar method for the rest of the sample. We use an arctangent function to estimate the circular velocity as a function of radius,

$$V(R) = V_0 + \frac{2}{\pi} V_c \arctan \frac{R}{R_i}, \quad (1)$$

which Courteau (1997) showed to be an adequate simple fit to galaxy rotation curves in the local universe. The disc models contain seven parameters: inclination i , position angle θ , coordinates (α, δ) of the disc centre, scale radius R_i , asymptotic velocity V_c , and systemic velocity V_0 .

To test how well these simple models can describe the data, we constructed velocity fields covering a large range of parameter space for each galaxy. From the disc centre, inclination, and position angle we compute the disc radius R at each pixel in the source-plane velocity maps via

$$R^2 = (x \cos \theta - y \sin \theta)^2 + \left(\frac{x \sin \theta + y \cos \theta}{\sin i} \right)^2,$$

where x and y are the distance from disc centre in right ascension and declination, respectively. We then calculate the circular velocity from equation (1), and correct for the azimuthal angle and inclination to obtain the observed velocity field of the model disc. To simulate lensing distortion, the models were then convolved with an elliptical point spread function estimated as the best two-dimensional Gaussian fit to the reconstructed tip-tilt reference star images. To estimate the goodness of fit, we compute the χ^2 statistic using the 1σ error from emission line fits. The emission line fits routinely yield a reduced χ^2_v close to unity indicating that these errors are a good estimate of the true uncertainty. To estimate uncertainty in the parameters, we perturb the model until the χ^2 increases by one standard deviation from the best fit. Best-fitting χ^2_v values for each galaxy are given in Table 2, except for C10949+5152 for which no reasonable fit was found. Velocity contours for the best-fitting disc models are shown in Fig. 2.

For galaxies which can be reasonably well described with disc-like kinematic structure, we extract the rotation velocity, inclination and disc position angle (major axis) from the model. The latter two values are usually estimated from morphology, but such methods are not necessarily accurate in this case due to the lensing distortion and asymmetric light distribution of these objects. The inclination and position angle estimated from morphology

Table 2. Source-plane properties of the lensed galaxies. Values for MACSJ2135–0102 are reported in Stark et al. (2008). Diameter is the extent of nebular emission except for MACSJ0712+5932 where it represents the extent of detected V -band emission, with uncertainty accounting for spatial resolution and errors in the lens model. The luminosity is compared to L^* for the LBG population at $z = 3$ (see text for methodology). Error in luminosity is 15–30 per cent dominated by the uncertain magnification. Velocity dispersion σ is taken as the flux-weighted mean. $V_{\text{max}} \sin i$ is computed as half the maximum peak-to-peak velocity from fits to the velocity field. Inclination i is the value relative to the plane of the sky for the best-fitting disc model, with uncertainty given as the range of parameter space within 1σ of the best fit. C10949+5152 is separated into the north-east and south-west merging components; no circular velocity is given since rotating disc models do not provide a good fit. Dynamical mass is calculated as $C R \sigma^2 / G$ using the diameter and dispersion values given in the table with $C = 5$ and error from R and σ , although the true uncertainty in M_{dyn} is roughly a factor of 2 due to unknown mass distribution and rotation support. Galaxy IDs (A, B, etc.) correspond to the labelled data points in Figs 5 and 6.

Galaxy (ID)	Intrinsic galaxy properties							
	Diameter (kpc)	L/L^*	SFR ($M_\odot \text{ yr}^{-1}$)	M_{dyn} ($10^9 M_\odot$)	σ (km s^{-1})	$V_{\text{max}} \sin i$ (km s^{-1})	i ($^\circ$)	χ^2_v
C10024+1709 (A)	20 ± 2	0.7	27 ± 6	55 ± 10	69 ± 5	76 ± 12	50^{+10}_{-30}	5.9
MACSJ0451+0006 (B)	5 ± 1	0.4	7 ± 2	19 ± 4	80 ± 5	38 ± 10	25^{+20}_{-10}	3.6
MACSJ0712+5932 (C)	1.5 ± 0.3	0.2	5 ± 1	5.7 ± 1.2	81 ± 2	15 ± 4	40^{+20}_{-25}	0.4
MACSJ0744+3927 (D)	2.0 ± 0.3	0.1	2.4 ± 0.5	11 ± 2	99 ± 4	129 ± 12	45^{+15}_{-25}	3.8
C10949+5152	7 ± 1	0.5	20 ± 6		66 ± 3			
NE (E1)	4.0 ± 0.6		13 ± 5	12 ± 2	71 ± 2			
SW (E2)	2.0 ± 0.3		7 ± 3	3.8 ± 0.6	57 ± 2			
MACSJ2135–0102 (F)	3.5 ± 0.3	1.5	40 ± 5	5.9 ± 1.0	54 ± 4	47 ± 7	55 ± 10	3.7

agree reasonably well for C10024+1704, MACS J0744+3927 and MACS J2135–0102 but are inconsistent with best-fitting disc models for MACS J0451+0006 and MACS J0712+5932. The morphological major axis in these systems is determined largely by the positions of a few bright clumps which dominate the luminosity. These clumps are likely to be misaligned with the kinematic major axis, which would explain the discrepancies observed. Similarly the clumpy, asymmetric luminosity distribution in these systems causes large uncertainties in estimates of the inclination. While smooth luminosity profiles can give accurate values of the inclination and position angle of disc galaxies, this approach is apparently not reliable for the clumpy systems common at high redshift. We therefore adopt the inclination and position angle from best-fitting disc models.

In Fig. 3, we show the one-dimensional velocity and dispersion profiles extracted from the data along a slit aligned with the disc position angle (or with the morphological major axis for the merger C10949+5153). This allows us to better quantify the kinematic structure and, particularly, to estimate an approximate rotational speed V_{\max} for each galaxy. The circular velocity is a parameter in the disc models, however, in some objects the velocity field does not reach an asymptotic value (e.g. MACS J0744+3927). In such cases the best-fitting value of V_c does not necessarily accurately represent the observed range of velocity. However, 4/5 galaxies in addition to MACS J2135–0102 display a coherent and roughly monotonic velocity curve consistent with the disc model. From these we estimate $V_{\max} \sin i$ as half of the range in the one-dimensional model profile in the region detected in H α emission, which provides a more reliable measure of the observed velocity range than the best-fitting $V_c \sin i$. Values of $V_{\max} \sin i$ as well as the best-fitting inclination from disc models are given in Table 2.

To estimate the dynamical mass for each galaxy, we adopt two approaches. First, we use the velocity dispersion and maximum extent of the H α emission and calculate $M_{\text{dyn}}(R) = C R \sigma_{\text{mean}}^2 / G$ with $C = 5$ appropriate for a sphere of uniform density and the radius is taken as half the maximum diameter. The geometrical factor C is likely between 3 and 10 for these highly turbulent galaxies (Erb et al. 2006). The dynamical mass is likely uncertain to within a factor of 2 due to the assumed geometry and exclusion of rotationally supported mass, whereas random uncertainty propagated from R and σ_{mean} is <25 per cent. We also use the velocity gradient to estimate the dynamical mass via $M_{\text{dyn}} \sin^2 i = R(V_{\max} \sin i)^2 / G$ but note that the maximum velocity shear in the sample gives $\Delta V / 2\sigma_{\text{mean}} \lesssim 1.5$ for all galaxies, so the rotational mass is less than half of the dispersion-supported mass before correcting for inclination. In future sections, we therefore typically adopt the dynamical mass calculated from velocity dispersion, noting that the total uncertainty is roughly a factor of 2 dominated by the assumed $C = 5$ with an additional systematic error due to the ignored rotational support. Adopted values of the diameter, dispersion and dynamical mass are given in Table 2.

Before we discuss what can be learned from the sample as a whole, we briefly review the results for each of the six galaxies in turn.

3.2 Review of individual properties

3.2.1 C10024+1709

After accounting for lensing amplification, the extent of H α emission is $\sim 10 \times 18$ kpc from our lens model, making this the largest object in our sample. The integrated H α emission line flux im-

plies an intrinsic $\text{SFR} = 27 \pm 6 \text{ M}_{\odot} \text{ yr}^{-1}$ (uncorrected for dust extinction).

The H α emission line and rest-UV morphologies both show a clumpy ring surrounding a fainter central region (Fig. 2), similar to that seen in some other massive, extended galaxies at high redshift (e.g. the $z = 2.26$ galaxy Q2643-BX482 in Genzel et al. 2008) as well as local ring galaxies (Romano, Mayya & Vorobyov 2008). The narrow ring, ~ 10 kpc diameter and misaligned central feature suggest that the ring of concentrated star formation was triggered by an on-axis collision with another galaxy, as opposed to dynamical resonances within the galaxy. This hypothesis is supported by the numerical simulations of Lynds & Toomre (1976) and identification of interacting companions to ring galaxies by Romano et al. (2008). Unfortunately, the H α emission in the central region coincides with a detector glitch in most of the IFU exposures and so the central dispersion and star formation density are only poorly constrained, with $\sigma = 50 \pm 21 \text{ km s}^{-1}$. In the ring, five UV- and H α -bright knots are resolved with similar isophotal radius, velocity dispersion and luminosity of $R \simeq 0.5$ kpc (for $L_{\text{H}\alpha} > 1.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$), $\sigma \simeq 45\text{--}65 \text{ km s}^{-1}$ and $L_{\text{H}\alpha} \sim 2 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$, with uncertainties from the lens model and emission line fits of ~ 40 per cent in radius, 15 per cent in dispersion and 30 per cent in luminosity. This implies a dynamical mass of the H α clumps from the velocity dispersion of $M_{\text{dyn}} = 2 \pm 1 \times 10^9 \text{ M}_{\odot}$ assuming uniform density, and a H α star-formation rate of $\text{SFR} = 2.0 \pm 0.7 \text{ M}_{\odot} \text{ yr}^{-1}$. The velocity field shows a smooth velocity gradient around the ring with peak-to-peak amplitude $2 V_c \sin i = 120 \pm 10 \text{ km s}^{-1}$. Using the axial ratio from the optical imaging, we estimate $\cos i = 0.6 \pm 0.1$ which suggests a rotationally supported mass $M_{\text{dyn}} = R V_c^2 / G = 2.1 \pm 0.8 \times 10^{10} \text{ M}_{\odot}$ within a radius of 9 kpc. If the galaxy has a uniform spherical mass distribution, then the observed dispersion suggests a larger dynamical mass of $5 \times 10^{10} \text{ M}_{\odot}$. The resolved star-forming regions in the ring thus account for about 50 per cent of the integrated H α flux and 15–25 per cent of the mass interior to the ring.

3.2.2 MACS J0451+0006

The integrated H α emission line flux suggests a star-formation rate of $\text{SFR} = 7 \pm 2 \text{ M}_{\odot} \text{ yr}^{-1}$, with the two brightest clumps (Fig. 2) contributing 0.8 ± 0.2 and $3.6 \pm 0.9 \text{ M}_{\odot} \text{ yr}^{-1}$. Some parts of the galaxy were not observed with OSIRIS due to the limited field of view and 20 arcsec extent of the arc. We expect these regions to contribute an additional $3 \pm 1 \text{ M}_{\odot} \text{ yr}^{-1}$ based on their rest-frame UV flux. The large magnification of this galaxy ($\mu = 49 \pm 11$) leads to an unprecedented 60 pc typical resolution in the source plane, providing unique insight into the kinematic structure of the star-forming regions. The H α velocity map reveals a coherent velocity field across the galaxy and within the clumps with a peak to peak amplitude of $80 \pm 20 \text{ km s}^{-1}$ (Fig. 3). The bi-symmetric velocity field together with the good disc model fit ($\chi^2_{\nu} = 3.6$) suggest that the kinematics of this system are likely dominated by rotation rather than merging.

3.2.3 MACS J0712+5932

From our IFU observations, only the brightest UV clump is detected in H α with an intrinsic star-formation rate of $\text{SFR} = 5 \pm 1 \text{ M}_{\odot} \text{ yr}^{-1}$ and we place limits on the remaining clumps of $\text{SFR} < 3 \text{ M}_{\odot} \text{ yr}^{-1}$ (3σ). The H α flux in the brightest clump is consistent with the total galaxy flux derived from long-slit spectroscopy, implying very

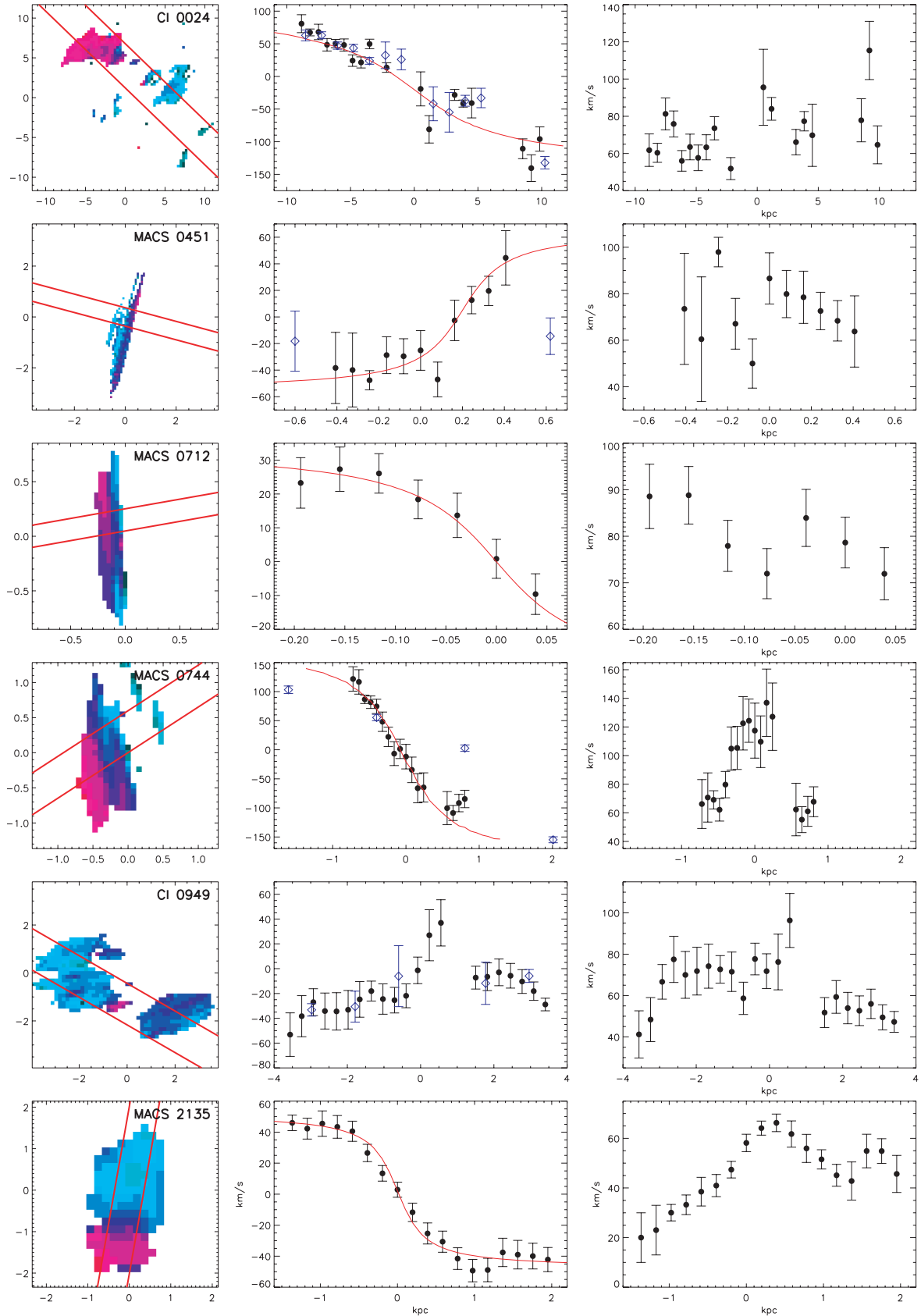


Figure 3. Left- to right-hand panels: velocity field, one-dimensional extracted velocity profile and equivalent velocity dispersion profile. Velocity and dispersion curves are extracted from left to right along the slit shown on the left figures. The rotation curve one would obtain in the absence of lensing with 0.15 arcsec resolution typical of AO-corrected observations is shown by the blue diamonds. Best-fitting profiles of the velocity field are shown in red. No model is shown for CI 0949+5153 since the velocity field is inconsistent with a rotating disc.

little star formation in the rest of the system. The two prominent UV-bright regions have FWHM sizes $\lesssim 0.5$ kpc and are separated by 1.5 kpc (Fig. 2). The H α emission in the brighter region exhibits a velocity gradient of 38 ± 8 km s $^{-1}$ along the highly sheared direction. While the disc model provides an excellent fit to the velocity field with $\chi^2_v = 0.4$, it is unclear whether the dynamical state of MACS J0712+5932 is dominated by rotation, merging or dispersion since only the strongest H α -emitting region is detected with OSIRIS. Assuming a uniform density within a radius of 0.2 kpc and $\sigma = 80 \pm 5$ km s $^{-1}$ we derive a dynamical mass of $M_{\text{dyn}} = 1.4 \pm 0.2 \times 10^9 M_\odot$ for the nebular emission region. The N[II] λ 6583 emission line is detected at the 2σ level in individual spatial pixels consistent with the flux ratio $N[\text{II}]\lambda 6583/\text{H}\alpha = 0.2$ observed in NIRSPEC long-slit spectra, with no measurable gradient in the flux ratio.

3.2.4 MACS J0744+3927

H α emission is detected across 2.0 kpc in the source plane and is resolved into 3 bright clumps in both the rest-frame UV continuum and H α . The two-dimensional velocity map clearly shows a bi-symmetric velocity field and is well described by the disc model with $\chi^2_v = 3.8$ and peak to peak amplitude of 280 ± 25 km s $^{-1}$, the largest observed in any high-redshift galaxy of this size (Fig. 3). The velocity dispersion varies from ~ 60 to 130 km s $^{-1}$ and peaks near the dynamical centre of the galaxy. This suggests a turbulent primitive disc with a total star-formation rate of $2.4 \pm 0.5 M_\odot \text{ yr}^{-1}$. The dynamical mass within a radius of 1 kpc is $M_{\text{dyn}} = R V_c^2 / G = 5 \pm 1 \times 10^9 M_\odot / \sin^2 i$ inferred from the velocity gradient or $M_{\text{dyn}} = 11 \pm 2 \times 10^9 M_\odot$ from the flux-weighted mean dispersion assuming uniform density.

The large rotation velocity, low SFR, and central dispersion peak conceivably make MACS J0744+3927 the most evolved disc-like galaxy of its size yet observed at high redshift and show that small, low mass ($\sim 10^{10} M_\odot$), turbulent field disc galaxies are already in place only 3 Gyr after the big bang.

3.2.5 C10949+5153

The reconstructed image of C10949+5153 at $z = 2.393$ shows two diffuse regions separated by $\simeq 3.9$ kpc, with the south-west component redshifted by 17 ± 6 km s $^{-1}$ from its companion (Fig. 3). Both components show resolved velocity gradients of order 30 and 100 km s $^{-1}$ but in opposite directions, indicating that these two regions are likely merging (this system cannot be described by a disc model). Each component is further resolved into multiple clumps of diameter 0.3–0.7 kpc within an isophote of $L_{[\text{O III}]} = 1.8 \times 10^{-16}$ erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$. Interestingly, while the clumpy [O III] morphology appears to correlate with the rest-frame UV, the ratio of rest-UV to nebular emission surface brightness varies considerably between clumps. This could be caused by non-uniform extinction or different star formation histories, since the rest-UV traces older star formation episodes than H α flux ($\lesssim 100$ and $\lesssim 20$ Myr, respectively). Assuming a global H β /[O III] flux ratio from long-slit spectra and case B recombination, the H β -derived SFR of the entire system is $20 \pm 6 M_\odot \text{ yr}^{-1}$ with 63 per cent of the nebular emission in the larger north-east region.

Dynamically, it appears that C10949+5153 is the only major merger in our sample, containing two spatially separated components with opposite velocity gradients and enhanced dispersion between components. From the velocity dispersion, we crudely esti-

mate that the north-east and south-west components have mass $12 \times$ and $4 \times 10^9 M_\odot$, respectively. Both of these components are fragmented further into multiple large clumps with seemingly coherent velocity fields.

3.2.6 MACS J2135–0102

For completeness, we also include in our sample discussion of the velocity field of LBG J2135–0102 (also known as the ‘Cosmic Eye’ due to its lensed morphology). Stark et al. (2008) show that the global dynamics suggest a thick galaxy disc in an early state of assembly with rotation speed (corrected for inclination) of $V_c = 67 \pm 7$ km s $^{-1}$ and $V_c/\sigma_r = 1.2 \pm 0.1$.

The source plane morphology of this galaxy comprises two distinct star-forming regions embedded in a rotating disc. The northern component has a diameter of ~ 0.8 kpc, a SFR of $21 \pm 3 M_\odot \text{ yr}^{-1}$ and a peak line width of 50 ± 5 km s $^{-1}$. Together, these suggest an intensely star-forming region with dynamical mass $M_{\text{dyn}} = 1.2 \pm 0.5 \times 10^9 M_\odot$. The southern component is brighter in the rest-frame UV, but has a lower H β -inferred SFR $= 11 \pm 2 M_\odot \text{ yr}^{-1}$. The diameter of 1.3 ± 0.3 kpc and peak line width of 65 km s $^{-1}$ suggest a mass $M = 3 \pm 1 \times 10^9 M_\odot$.

3.3 Properties of the ensemble

Having discussed the sources individually, we now turn to general conclusions based upon their integrated properties as listed in Table 2.

3.3.1 Kinematics

All six objects in our sample show well-resolved velocity structure. A visual inspection of Figs 2 and 3 reveals that four galaxies (C10024+1709, MACS J0451+0006, MACS J0744+3927 and MACS J2135–0102) have smooth velocity gradients suggesting ordered rotation whilst C10949+5153 appears to be a merger with both components showing well-resolved velocity gradients. The dynamical state of MACS J0712+5932 is unclear since only the brightest H α -emitting region is detected with OSIRIS. The nebular emission shows a smooth velocity gradient in MACS J0712+5932, but subtends only four resolution elements in the most highly magnified of the three images and so it is unclear whether the kinematics of MACS J0712+5932 are dominated by rotation, dispersion or merging.

For the galaxies studied here, the best-fitting disc models have χ^2_v values which range from 0.4 to 5.9 with a mean of 3.5, indicating agreement typically within 2σ for individual pixels. For reference, disc models for 18 galaxies in the Spectroscopic Imaging Survey in the Near-Infrared with SINFONI (SINS) sample which show the most prominent rotation yield best-fitting χ^2_v values of 0.2–20 to the models of Cresci et al. (2009), so our simple model provides an equally good fit to the lensed galaxies. All galaxies show small-scale deviations from the model as indicated by the typical $\chi^2_v > 1$; these proper motions could be caused by the effects of gravitational instability or simply be due to the unrelaxed dynamical state indicated by high velocity dispersions $\sigma > 50$ km s $^{-1}$. We therefore conclude that the model provides an adequate fit to the data and that the velocity fields are consistent with the kinematics of a turbulent rotating disc, except in the case of C10949+5152.

It is illustrative to demonstrate the dramatic improvement in our understanding of the internal dynamics of our sources that arises

uniquely through the improved spatial sampling enabled by studying strongly lensed galaxies. To do this we bin the source-plane data cubes of our targets to a coarser resolution typical of that achievable for *unlensed sources* observed with an AO-corrected resolution of 0.15 arcsec. We then re-fit the emission lines and extract one-dimensional velocity profiles using the same methods as adopted for the original data. Since the lensing magnification results in μ times more flux spread over μ times as many pixels, the binned signal-to-noise ratio is a factor of $\sqrt{\mu}$ higher than equivalent observations of unlensed versions of our galaxies. These simulations therefore represent non-lensed galaxies observed for much longer integrations (~ 100 hours!). Even so, the resulting velocity profiles (also shown in Fig. 3) are considerably inferior to those of our lensed data. A credible rotation curve is only retrieved for CI0024+1709, our least magnified galaxy, with important kinematic detail lost in all other objects (for example, MACS J0712+5932 is unresolved). Such poor spatial sampling is insufficient to distinguish between rotation and merging. More quantitatively, velocity gradients in all of our objects except CI0024+1709 are significantly underestimated (typically $V_{\text{max,non-lens}}/V_{\text{max,lens}} = 0.6 \pm 0.2$).

3.3.2 Physical characteristics: size, luminosity and mass

Next, we examine the integrated physical properties of the lensed galaxies. First, we briefly compare the luminosity, size and mass to the general Lyman-break population at $z \simeq 2-3$. In Fig. 4, we compare the distribution of apparent R -band magnitudes for our sample to that of the Lyman-break population at $z \sim 3$ (Shapley et al. 2001). The comparison demonstrates that five of our six galaxies are fainter than L^* , ranging from 0.1 to 1.5 L^* , with median 0.5 L^* well below that of other spatially resolved IFU studies. The intrinsic $H\alpha$ flux of the arcs is also lower than in other surveys, with a mean and median inferred SFR of $17 M_{\odot} \text{ yr}^{-1}$ (Table 2) compared to 26–33 $M_{\odot} \text{ yr}^{-1}$ in Law et al. (2009) and Förster Schreiber et al. (2009). Comparing the typical spatial extent of the nebular emission to other surveys, the median radius (extent of detected nebular emission) and dynamical mass of the lensed sample are 2.1 kpc and $1.3 \times 10^{10} M_{\odot}$, somewhat more extended than the compact galaxies studied by Law et al. (2009) which have median radius of 1.3 kpc and $M_{\text{dyn}} = 0.7 \times 10^{10} M_{\odot}$. Turning to the dynamics, the flux-weighted mean velocity dispersions σ_{mean} are perfectly consistent

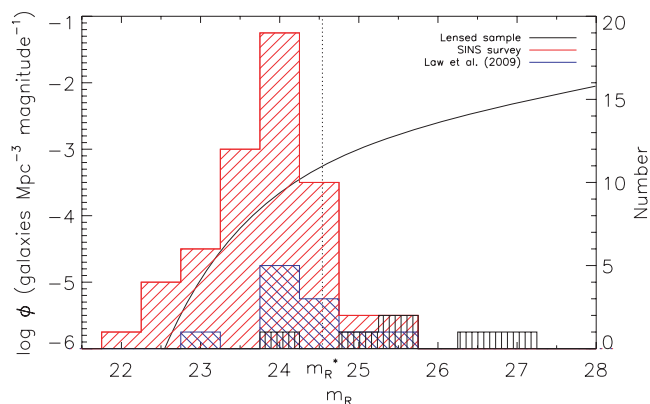


Figure 4. Apparent R -band luminosity function of $z \sim 3$ LBGs from Shapley et al. (2001) compared to the distribution of suitably corrected apparent R magnitudes for our lensed sample as well as the SINS (Förster Schreiber et al. 2009) and Law et al. (2009) samples. We compute the apparent R magnitudes of the IFU samples at $z = 3$ for an effective wavelength $\lambda = 600\text{--}800$ nm depending on the available photometry.

with those studied by Law et al. (2009): both samples span a range of 50–100 km s^{-1} with mean and median 70–75 km s^{-1} , indicating that the two sets of galaxies probe the same range of dynamical mass density. We note that the median $H\alpha$ FWHM (from long-slit spectra; Erb et al. 2006) and stellar mass of $\simeq 6$ kpc and $2.9 \times 10^{10} M_{\odot}$ are a better representation of the Law et al. (2009) sample as they do not depend on sensitivity of the data. The SINS survey probes somewhat more extended objects, with median $H\alpha$ FWHM and stellar mass of $\simeq 8$ kpc and $M_{\star} \simeq 3 \times 10^{10} M_{\odot}$. The mass density and extent of nebular emission of the lensed galaxies are therefore comparable to the more luminous Law et al. (2009) sample and somewhat lower than in the SINS survey. The lensed galaxies are also below the average size and mass for L^* systems at similar redshifts, with the notable exception of CI0024+1709.

Our high-resolution data enable us to determine reliable dynamical properties and compare with other IFU observations. In particular, we can examine the prevalence of dispersion and rotation as a function of size and dynamical mass. Law et al. (2009) report evidence for dispersion-dominated kinematics in compact low-mass galaxies in contrast to the \sim equal mix of rotation, dispersion and complex/merger kinematics found in the SINS survey (Förster Schreiber et al. 2009), although the dispersion-dominated fraction is higher for more compact SINS galaxies. However, this claim is hampered by the small number of resolution elements ($\simeq 2\text{--}4$) subtended by each source (although see Epinat et al. 2010). We can address this issue with the superior resolution offered by gravitational lensing. The relevant relations between V/σ and size or dynamical mass is shown in Fig. 5 for the five lensed galaxies which are reasonably well fit by disc models compared to the compact LBGs from Law et al. (2009) and the rotation-dominated SINS galaxies described by Cresci et al. (2009), showing that the ratio of velocity shear to dispersion is higher for larger, more massive galaxies. Furthermore, the general agreement between the lensed sample and other comparison samples is also shown in Fig. 5 and demonstrates that the dynamics of sub- L^* star-forming galaxies do not differ substantially from more luminous objects.

Noting that many galaxies do not reach an asymptotic velocity within the region probed by our IFU observations, it is likely that larger circular velocities exist in faint outer regions of these galaxies. Indeed, the spatial extent and mass inferred from long-slit spectra and photometry are higher than from relatively shallow IFU data. We therefore also compare the observed velocity gradient and, where appropriate, inclination-corrected rotational velocity as a function of size and dynamical mass in Fig. 5. The observed velocity gradients of 3/5 lensed galaxies and the entire comparison sample are within 0.3 dex of the median value $V_{\text{shear}}/R = 25 \text{ km s}^{-1} \text{ kpc}^{-1}$. The consistent velocity gradients and corresponding V_{shear}/σ obtained with a typical $\sigma = 75 \text{ km s}^{-1}$ (Fig. 5) suggest that the extended structure in some of the compact objects may in fact host velocity fields comparable to the larger disc galaxies.

While MACS J0451+0006 and MACS J2135–0102 have velocity gradients consistent with the other samples considered here, the clear outlier MACS J0744+3927 demonstrates that at least some small galaxies at this redshift have significant dynamical support from ordered rotation. This galaxy has an inclination-corrected $V_c/\sigma = 1.8^{+1.2}_{-0.4}$ at radius $R = 1$ kpc and a $H\alpha$ -derived star-formation rate surface density $\Sigma_{\text{SFR}} = 0.8 \pm 0.3$, which is a factor of 3 lower than any galaxy in the dispersion-dominated sample, possibly indicating a later stage of evolution.

Motivated by the relatively large velocity shear and small Σ_{SFR} of MACS J0744+3927, we explore the possibility that the low V/σ observed in many compact galaxies is an effect of selecting galaxies

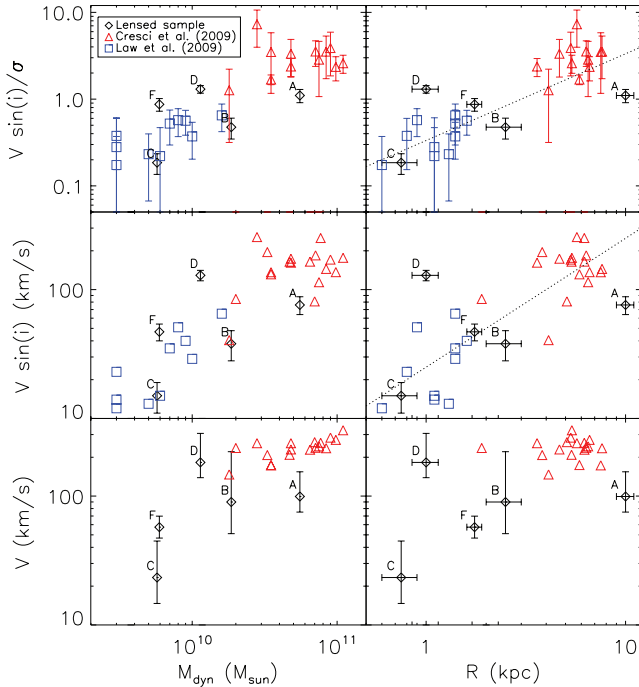


Figure 5. Kinematics as a function of dynamical mass and radius. The median $V \sin i / R = 25 \text{ km s}^{-1} \text{ kpc}^{-1}$ is plotted in the middle right panel, and the corresponding V/σ for typical $\sigma = 75 \text{ km s}^{-1}$ is shown in the upper right. Data for the lensed sample are given in Table 2 and labelled accordingly. Data for the comparison samples are taken from tables 3 and 4 of Law et al. (2009) and table 2 of Cresci et al. (2009), and are discussed in Section 3.3.2. We note that the dispersions σ_0 from Cresci et al. (2009) are systematically smaller than σ_{mean} used for the other data sets. σ_0 is better estimated by a simple average of dispersion values, which is typically 5 per cent smaller than a flux-weighted mean for the lensed galaxies.

in early stages of evolution with large dispersions and SFRs. This is expected in models of star formation feedback, which predict that mechanical energy introduced by supernovae leads to higher velocity dispersion and hence lower V/σ as Σ_{SFR} increases. In one such model, Dib, Bell & Burkert (2006) simulate the velocity dispersion within the interstellar medium of galaxies induced by supernovae energy injection (assuming a 25 per cent feedback efficiency) and predict a correlation between star-formation surface density and velocity dispersion.

To test whether supernova feedback might be responsible for the high dispersion observed in all $z \gtrsim 2$ star-forming galaxies, we show the velocity dispersion σ as a function of Σ_{SFR} in Fig. 6. For the range of Σ_{SFR} with modelled supernova feedback, the observed velocity dispersions $\sigma = 30\text{--}80 \text{ km s}^{-1}$ are much higher than the predicted $\sigma = 10\text{--}15 \text{ km s}^{-1}$. We note that the density used in these simulations is $\sim 30\times$ lower than inferred for the $z \simeq 2$ galaxies, so the simulated dispersion is likely overestimated by a factor of ~ 5 . While the data show a slight trend of σ increasing with Σ_{SFR} , the observed relation is inconsistent with simulations. We therefore conclude that supernova feedback is insufficient to explain the observed velocity dispersions. Fig. 6 shows the relation between V/σ and Σ_{SFR} , clearly demonstrating that V/σ decreases with Σ_{SFR} . However, this trend is likely ultimately due to the velocity–size relation: larger galaxies tend to have larger rotation velocities (Fig. 5) and smaller Σ_{SFR} (Fig. 6). This is explained by different sensitivities of the data, as deeper spectra (lower Σ_{SFR}) reveal more extended structures at larger radius with larger rotation speed. The velocity–

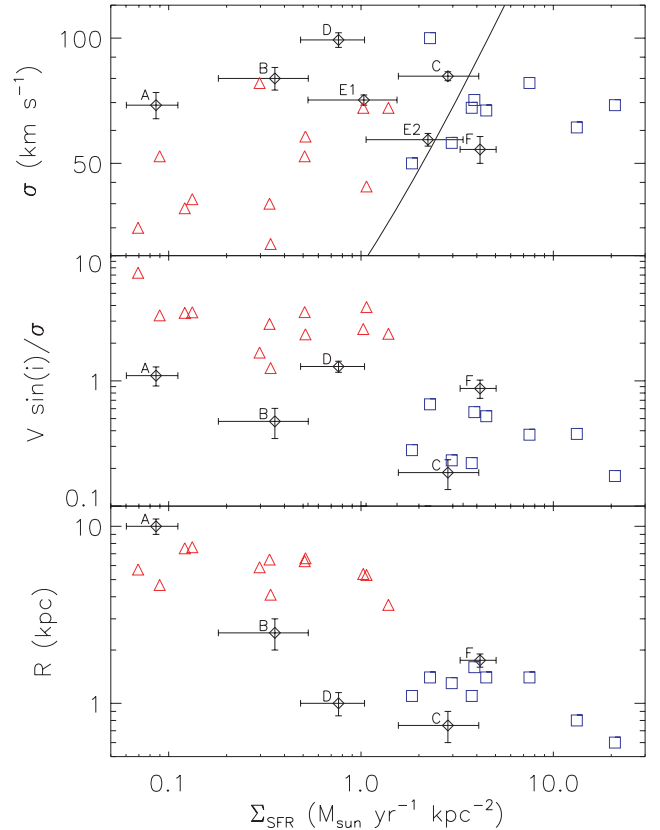


Figure 6. Velocity dispersion, V_{shear}/σ , and radius as a function of SFR density estimated from $\text{H}\alpha$ flux. Symbols are the same as in Fig. 5. The solid line in the top panel is a fit to simulations; see text for details. The observed σ is inconsistent with the simulations. Dispersion is at best weakly correlated with Σ_{SFR} . The strong correlation of radius and σ/V_{shear} with Σ_{SFR} is likely due to different sensitivity of the observations.

size correlation contributes much more to the observed V/σ – Σ_{SFR} relation than any correlation between Σ_{SFR} and the velocity dispersion. These data thus do not support the hypothesis that V/σ is strongly affected by the density of star formation: σ increases by less than a factor of 2 over two orders of magnitude in Σ_{SFR} .

3.4 Star-formation scales within discs

The small $V_{\text{max}}/\sigma \leq 1.8$ and clumpy morphology of all galaxies suggest that the rotating discs are highly turbulent and may be dynamically unstable. We therefore explore the scalelengths for gravitational collapse within the high-redshift disc galaxies.

Evidence is accumulating that the mode of star formation may be very different in early systems compared to that seen locally (Elmegreen & Elmegreen 2005; Bournaud et al. 2008). Rather than forming stars within giant molecular clouds (GMCs) which condense out of a stable galaxy, star formation may be triggered by fragmentation of a dynamically unstable system. Briefly, in a rotating disc of gas and stars, perturbations smaller than a critical wavelength L_{max} are stabilized against the inward pull of gravity by velocity dispersion while those larger than some L_{min} are stabilized by centrifugal force. If the dispersion and rotation velocity are too low, $L_{\text{min}} > L_{\text{max}}$ and perturbations of intermediate wavelength grow exponentially. This interplay is summarized by the Toomre parameter $Q = L_{\text{max}}/L_{\text{min}}$ which is calculated from the velocity dispersion, rotation curve and mass distribution (Toomre 1964). Galaxies with $Q < 1$ are

therefore unstable on scales between L_{\max} and L_{\min} and will fragment into giant dense clumps. This could trigger star formation in clouds of much higher mass and radius than GMCs in local spiral galaxies with $Q > 1$, and can explain the clump-cluster and chain morphologies observed in many high-redshift galaxies. Dynamical friction, viscosity and tidal interactions may cause these clumps to migrate towards the centre of the galaxy potential, forming a bulge which stabilizes the system against further fragmentation.

From the galaxies whose velocity fields can be reasonably well described by rotating systems, we calculate the Toomre parameter via

$$Q = \frac{\sigma_r \kappa}{\pi G \Sigma}, \quad (2)$$

which describes the stability of a rotating disc of gas. If $Q < 1$ the system is unstable to local gravitational collapse and will fragment into overdense clumps. The value of κ is somewhat uncertain as it depends on the unknown mass distribution; our observations are consistent with a range $\sqrt{2}(V_c/R) - 2(V_c/R)$ corresponding to constant V_c and $V_c \propto R$, respectively. Adopting $\kappa = \sqrt{3}V_{\max}/R$ appropriate for a uniform disc and using dynamical mass to estimate the surface mass density Σ , we find an inclination-corrected $Q \lesssim 0.6$ for all galaxies in our sample. We estimate that the uncertainty in Q is dominated by a factor of $\simeq 2$ error in the dynamical mass. The assumed κ introduces a negligible 15 per cent uncertainty, with an additional random error of ~ 30 per cent from the input parameters. Disc thickness and stellar abundance also affect the value of Q . Combined, these effects result in roughly a factor of 2 uncertainty. Even so, these galaxies all appear to be dynamically unstable since $Q < 1$. Hence, we expect them to fragment into massive clumps on scales of order the Jeans length for dispersion support. In a uniform disc, the largest scale for which velocity dispersion stabilizes against gravitational collapse is

$$L_J = \frac{\pi \sigma^2}{8G\Sigma}, \quad (3)$$

which is readily estimated from the dispersion and dynamical mass density. As with Q , the uncertainty in L_J is a factor of $\simeq 2$ dominated by the dynamical mass with additional uncertainty from the unknown mass distribution, disc height, stellar content and directional dependence of σ . The resulting instability scale is 1–3 kpc for CI0024+1709 and 0.1–1.5 kpc for all other objects, consistent with the observed clump sizes.

4 STAR-FORMING REGIONS AT HIGH REDSHIFT

For each galaxy in our sample, the gain in resolution provided by gravitational lensing reveals multiple resolved giant H II regions which, as a group, dominate the integrated SFR. This gain enables us to study, in more detail than hitherto, the properties of individual star-forming complexes in typical high-redshift galaxies. In the following analysis, we concentrate on those H II regions with extended bright emission which are sufficiently isolated. Ideally, we would construct a complete well-defined sample, however, in the exploratory work presented here we wish to limit the sample to objects for which the size and flux can be measured robustly. We therefore specifically exclude H II regions with overlapping emission in the H α emission line maps (such as those in MACSJ0744+3927).

In brief, H II regions were selected with a flux isophote in the image plane where the instrumental response is well known. Thus, we can check whether each H II region is sufficiently resolved by comparing with the point-spread function produced by a bright

tip-tilt reference star. To measure the area, each H II region was deconvolved with the point spread function using a method which accounts for the distorted shapes produced by gravitational lensing. The intrinsic flux and area were then computed by reconstructing the H II region in the source plane.

H II regions were selected above a flux isophote corresponding to $\simeq 3\sigma$, where σ is the noise level measured in narrow-band images, constructed by collapsing continuum-subtracted OSIRIS data cubes around the strongest emission feature. Only isolated H II regions (in which there is a single local maximum within the isophote) were selected. Regions not meeting this criterion are excluded from this analysis since attempting to disentangle multiple confused sources would introduce a large uncertainty. The isophote used varies from 1.4 to $4.6 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ for different arcs. The isophote for each selected H II region is shown in Fig. 2. Each H II region subtends 0.5–0.9 arcsec in the image plane, with the notable exception of the giant clump in MACSJ0451+0006 which spans 3.2 arcsec. The selected H II regions are all well-resolved since the point spread function has $\text{FWHM} \leq 0.2$ arcsec in all observations.

For each H II region we calculated the total nebular line flux and intrinsic angular size in the image plane. The luminosity of each H II region was taken as the total flux within the selection isophote, with the uncertainty determined from the noise level in the narrow-band image. The H II region size is more complicated to derive since the effect of the spatial resolution needs to be taken into consideration. We proceed by making two basic assumptions. First, we assume the observed flux distribution is a convolution of the actual distribution with the instrumental point spread function. We can therefore compute the approximate intrinsic spatial variance by subtracting the Gaussian point spread function (PSF) variance from the measured variance within the isophote, $V_{\text{int}} = V_{\text{iso}} - \sigma_{\text{PSF}}^2$. This is equivalent to subtracting $\sigma = \text{FWHM}/2.35$ in quadrature from Gaussian profiles, but the procedure is applicable to non-Gaussian asymmetric distributions. In all cases $V_{\text{iso}} > \sigma_{\text{PSF}}^2$ confirming that the H II regions are well resolved: $V_{\text{iso}}/\sigma_{\text{PSF}}^2 = 2.3$ for one H II region and ≥ 3.2 for all others. Secondly, we assume that the isophotal area scales with spatial variance such that intrinsic surface area $A_{\text{int}} = A_{\text{iso}}(V_{\text{int}}/V_{\text{iso}})$, where A_{iso} is defined as the pixel size multiplied by the number of pixels within the isophote. Uncertainty in the isophotal flux ranges from 12 to 27 per cent propagated from flux calibration and noise level in the narrow-band image. The uncertainty in A_{iso} is estimated by assuming an error of PSF σ for the isophote diameter. The range of resulting angular diameter ($2\sqrt{A_{\text{iso}}/\pi}$) and relative error is 0.12 ± 0.06 to 0.61 ± 0.08 arcsec.

To determine the source plane properties, each H II region is finally reconstructed using the lens model transformation. The total magnification μ is calculated from the ratio of image- to source-plane flux. The source plane diameter is then defined as $d = 2\sqrt{(A_{\text{iso}}/\mu\pi)}$. This method is robust against the spatially varying magnification of the lensed arcs. Uncertainty in the lens model has little effect on the diameter but significantly contributes to the error in flux. From the H α flux (converted from [O III] $\lambda 5007$ for CI0949+5153) we estimate the SFR using the Kennicutt (1998) prescription. The values range from 0.8 to 3.6 $M_{\odot} \text{ yr}^{-1}$ SFR and 0.3–1.0 kpc diameter.

From the source plane diameters and kinematic data, we estimate the dynamical mass of the H II regions. We use the flux-weighted mean velocity dispersion within the clump σ_{mean} and assume a uniform spherical mass distribution ($C = 5$) as discussed in Section 3.1. The H II regions have large flux-weighted mean dispersions, with σ_{mean} ranging from 45 to 80 km s^{-1} . The dynamical masses range from 0.7 to $3 \times 10^9 M_{\odot}$, far greater than typical star-forming

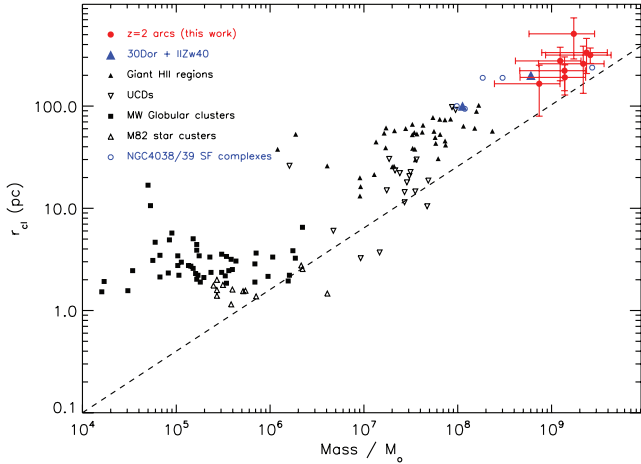


Figure 7. Size versus dynamical mass of individual star-forming regions within our high-redshift sample, compared to local star clusters and H II regions. The high-redshift H II regions have size and mass consistent with the largest star-forming complexes in the local universe. Local data are taken from Harris (1996) and Pryor & Meylan (1993) for Galactic globular clusters; Hasegan et al. (2005), Hilker et al. (2007) and Evstigneeva et al. (2007) for ultra-compact dwarf galaxies; McCrady & Graham (2007) for M82 clusters; Fuentes-Masip et al. (2000) for giant H II regions; and Bastian et al. (2006) for star-forming complexes in the Antennae. The dashed line represents a model for regions which are optically thick to far-infrared radiation and have undergone adiabatic expansion (Murray 2009). Dynamical mass for the high-redshift data is calculated as $M_{\text{dyn}} = C(R\sigma^2/G)$ with assumed $C = 5$ appropriate for a uniform-density sphere. The mass error bars account for statistical uncertainty in R and σ .

clusters in the local universe. Statistical uncertainty in the dynamical mass is 20–60 per cent, so the additional factor of ~ 2 systematic uncertainty in C contributes significantly to the dynamical mass estimate. The mass–radius relation of the high-redshift clumps is shown in Fig. 7 along with a sample of local star clusters and giant H II regions for comparison. This shows that the H II regions studied here are comparable in size and mass to the largest local star-forming complexes and consistent with the mass–radius relation observed locally.

In Fig. 8, we compare the size–luminosity relation of these star-forming regions with equivalent data observed locally (from Gonzalez Delgado & Perez 1997 for normal spirals, and Bastian et al. 2006 for intense starbursts such as the Antennae) and with a lensed arc at $z = 4.92$ (Swinbank et al. 2009). The sizes observed in the high-redshift galaxies are comparable to the largest local star-forming (H II) regions but with $\sim 100\times$ higher SFRs than in local spiral galaxies. However, the implied SFR densities are roughly consistent with that observed in the most vigorous local starbursts. This result is not significantly affected by the resolution of different observations, although varying the selection isophote alters the radius–luminosity relation. We note that the flux isophotes used to define H II regions in local spirals are much lower, so to quantify this effect we extract individual H II regions from narrow-band H α images of local galaxies from the *Spitzer* Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003) and 11 Mpc H α and UV-traviolet Galaxy Survey (11HUGS; Lee et al. 2007) using various isophotes. The effect on the size–luminosity relation as the isophote is increased is shown in Fig. 8 as the vector A, which demonstrates that the extracted regions become smaller with higher average surface brightness. The vector B shows the effect of degrading the resolution while the isophote is kept fixed, which causes distinct

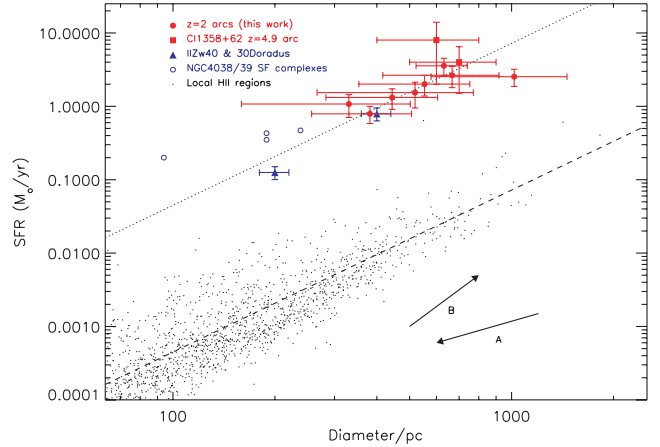


Figure 8. H α -inferred SFR as a function of H II region size. Red circles represent individual H II regions from our lensed sample. Cl 0949+5152 was observed in [O III] with the H α flux taken to be 1.2 times the [O III] λ 5007 flux as determined from long-slit NIRSPEC observations. The value for MACS J2135–0102 was determined from the H β flux assuming case B recombination. The SFRs are all derived from H α luminosities using the Kennicutt (1998) prescription. Red squares are from the lensed $z = 4.92$ galaxy presented by Swinbank et al. (2009), black points are H II regions in local spiral galaxies from Gonzalez Delgado & Perez (1997), and blue open circles are star cluster complexes in the interacting galaxies NGC 4038/4039 from Bastian et al. (2006). The vectors A and B are explained in the text. The dashed line shows a fit to the data from local spiral galaxies, and the dotted line is the same but increased by a factor of 100 times in SFR density. The high-redshift star-forming regions have significantly higher density of massive stars than H II regions in nearby spirals, but are comparable to the brightest star cluster complexes found in the local universe.

H II regions to merge together giving the appearance of a larger region with similar surface brightness. Since the surface brightness of the high-redshift H II regions is $\sim 100\times$ higher than in local spirals, we conclude that the offset cannot be explained by different resolution and sensitivity of the various data sets. Metallicity also fails to explain the offset, as demonstrated by MACS J2135–0102 which has an R_{23} index and C IV P Cygni profile suggesting 0.4–1 Z_{\odot} metallicity (Stark et al. 2008; Quider et al. 2010). This implies that the luminosities in the high-redshift H II regions are truly much larger than in local spirals. Furthermore, the observed diameters are consistent with the Jeans length for support by velocity dispersion, suggesting that they collapsed as a result of disc instabilities. We expect this to occur since the Toomre Q parameter is less than unity for all galaxies in our sample. It therefore seems likely that intense star-formation in high-redshift galaxies is driven by the fragmentation of gravitationally unstable systems.

5 CONCLUSIONS

We have utilized strong gravitational lensing together with laser-assisted guide star adaptive optics at the Keck observatory to study the internal characteristics of six $z = 1.7$ – 3 star-forming galaxies with a spatial resolution down to ~ 100 – 200 parsec. Extending beyond the diffraction limited capability of current 8–10 m class telescopes, our study provides an interesting preview of the science that will routinely be possible with future 30 m class optical/infrared telescopes with adaptive optics systems. We demonstrate that enhanced resolution allows us to resolve morphological and kinematic structure which has not been (and cannot be) discerned in AO-based surveys of similar non-lensed sources. In particular, we

resolve multiple giant star-forming regions of size consistent with that expected from Toomre instability in *all* of our targets (including separate merging components). Furthermore, we determine the dynamical state of galaxies which would be too poorly sampled to distinguish between rotation, merging or dispersion-dominated kinematics without gravitational lensing.

The lensed sample allows a unique study of relatively faint and small galaxies at high resolution. The median luminosity of the sample is half of the characteristic L^* for $z = 3$ LBGs and well below that of other high-redshift IFU studies. We find that the kinematics of the sub- L^* population are in general agreement with larger and more luminous galaxies at similar redshifts: four of the six systems are clearly rotating with $V \sin i / \sigma = 0.5\text{--}1.3$, one has a velocity gradient consistent with rotation within the small H α -bright region of the arc detected with OSIRIS, and one is a major merger. All have high velocity dispersion $\sigma = 50\text{--}100 \text{ km s}^{-1}$, consistent with all other resolved observations of $z > 2$ star-forming galaxies and comparable to the value $\sigma \simeq 50 \text{ km s}^{-1}$ for stars which formed in the Galactic disc at $z \simeq 2$ (Sparke & Gallagher 2000). Galaxies with a larger radius of detected nebular emission tend to have higher velocity shear and V/σ and lower Σ_{SFR} ; these trends are consistent with other observations. The case of MACS J0744+3927 with inclination-corrected $V = 180^{+100}_{-40} \text{ km s}^{-1}$ clearly demonstrates that some small ($R = 1.0 \pm 0.2 \text{ kpc}$), fast-rotating field disc galaxies are already in place by $z = 2$. Well-sampled velocity fields demonstrate that the ubiquitous giant clumps are often embedded in common rotating systems and are not independent merging components. In contrast, non-lensed clumpy systems with velocity shear have been interpreted as mergers or remained ambiguous. These results demonstrate the need of high-resolution observations to distinguish rotating systems and mergers, as well as to probe the $< 1 \text{ kpc}$ scale of star formation at high redshift.

The observations presented here represent the best current probe of the scale of star formation at $z \gtrsim 2$ and, as such, can be compared to theoretical predictions. Most of the star formation in our sample occurs within giant H II regions of diameter $0.3\text{--}1 \text{ kpc}$ comparable to the largest local H II regions, with SFR density comparable to the most vigorous local starbursts and $\sim 100\times$ higher than in typical spiral galaxies. This offset in Σ_{SFR} cannot be explained by the different resolution or sensitivity of low- and high-redshift observations. Only one of our six objects is a clear major merger with both merging components broken into high-SFR clumps, suggesting that star formation episodes in sub- L^* high-redshift galaxies are triggered by Toomre instability independent of major merger events. We note that the merging system demonstrates no enhancement in star formation (as traced by nebular emission) compared to the non-merging galaxies. The increased high-mass star formation relative to local spirals likely results from some combination of higher gas density, increased star formation efficiency, shorter star formation time-scales, and possibly other effects. The clumpy star formation, high Σ_{SFR} , kinematics consistent with rotation and small $Q < 1$ are in qualitative agreement with the galaxy evolution model of Dekel et al. (2009) in which galaxies accrete their baryonic mass from cold streams. In this model, the clumps form due to Toomre instability in turbulent discs and migrate into the galaxy centre on time-scales of a few hundred Myr, forming a bulge which stabilizes the system and increases the star formation time-scale after $\sim 2 \text{ Gyr}$. Numerical simulations suggest that cold-stream accretion is a dominant mechanism in galaxy assembly, especially at early times and in galaxies with halo masses less than a few $10^{11} M_{\odot}$ (Ocvirk, Pichon & Teyssier 2008; Brooks et al. 2009; Kereš et al. 2009), although we note that there is no observational evidence for

these cold streams. In particular, the high-resolution simulations of Brooks et al. (2009) show that accretion of cold gas dominates the build-up of stellar discs and bulges in sub- L^* galaxies and allows disc formation at earlier times than if the accreted gas is shock-heated. The rotating kinematics and distribution of star formation in the lensed sample therefore supports, at least qualitatively, a cold gas accretion scenario for galaxy formation.

Analysis of our sample has shown the benefit of using lensed sources to probe the inner structure of early star-forming galaxies. The advent of many panoramic multi-colour imaging surveys will hopefully reveal many further examples of such systems, ensuring further progress with laser-assisted guide star adaptive optics. Ultimately, the next generation of 30-m optical/near-infrared telescopes will extend the high-resolution studies presented herein to the entire population of high-redshift star-forming galaxies.

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